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KAIFER AEROSPACE & ELECTRONICS

**Palo Alto Electronics Plant
Palo Alto, California**

**EXPERIMENTAL EVALUATION
OF
HEAD-UP DISPLAY
HIGH BRIGHTNESS REQUIREMENTS**

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FOREWORD

This report is an abridged excerpt from a study made in April 1965 entitled: Human Factors Report on the Vertical/Head-up Display, by C. R. Kelley, J. D. Goff, and P. H. Strudwick of Dunlap and Associates, Inc. and J. M. Ketchel of Kaiser Aerospace and Electronics.

The experimental design was originated by Kelley and Strudwick for V/HUD prototype equipment utilization. Their plan was modified at Kaiser by Ketchel and R. W. Way who designed and constructed the symbol generating apparatus described herein.

Experiments were conducted at the Kaiser Palo Alto facility by the authors. Subjects were selected Kaiser personnel with the exception of Mr. Strudwick who served alternately as subject and experimenter.

ABSTRACT

The HUD, or Head-up part of Kaiser's Vertical/Head-up Display, is an avionics device that collimates and projects symbology onto the real world at infinity. It enables a pilot to look through the aircraft windscreen while viewing command and status information without requiring visual accommodation changes.

This experiment was undertaken to determine what symbol brightness is required to use the Head-up Display under high background brightness conditions. The anticipated worst situation (other than looking directly into the sun) consists of flight over sunlit clouds or snow, in which case there could be continuing background brightnesses on the order of 10,000 foot lamberts against which the display must be seen.

Results indicate that pilots will want display contrasts of at least 20 to 35 per cent, i. e. , perhaps 1800 to 3500 ft. L. display brightness reflecting from the HUD combining glass, assuming 90 per cent transmission by windscreen and combining glass and an external background luminance of 10,000 ft. L. The minimum brightness contrast for a barely visible, near-threshold display is on the order of 10 per cent, or 900 to 1,000 ft. L. reflected from the combiner.

This will provide an extremely dim display, but one that most pilots can be expected to see more than 90 per cent of the time.

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INTRODUCTION

One of the severe visual problems associated with a windscreen, combining glass, projection-type display, such as the Kaiser Head-up Display (HUD), consists of flight over sunlit clouds or snow. As an anticipated worst case condition, there could be continuing background brightnesses on the order of 10,000 foot lamberts against which the display must be seen.

Optical projection and collimating requirements can be such that most of the display cathode ray tube emitted light is lost through the combining glass. For example, a clear non-coated combiner might require that 10,000 ft. L. be generated at the CRT to reflect 1,000 ft. L. to the pilot. It can be seen that the CRT would be subjected to harsh demands under such conditions and a 1,000 ft. L. brightness against a 10,000 ft. L. background is itself of questionable utility.

Data are not available on the effects of operating cathode ray tubes in the 10,000 ft. L. region or beyond, but it appears likely that phosphor burn would occur within a few hours, and perhaps even within minutes. It is thus believed to be impractical to operate a CRT in the range of brightnesses believed necessary. With a clear combining glass, the display might even be invisible at the lower brightnesses. For these reasons, the Head-up Display brightness problem is considered to be critical.

Search of standard reference sources (Tufts Handbook, 1961 and 1963; Wulfeck, et al., 1958; Stevens Handbook, 1951; McFarland, 1953; Linkzy, 1950; and Morgan, et al., 1963) failed to provide a definitive answer to Head-up Display brightness requirements since few studies go to 10,000 ft. L., and none have employed targets directly comparable to HUD displays. Perhaps the most comparable is a much quoted study by Steinhardt (1936), which indicates, for example, that the ratio of added brightness to background brightness to make a square of 31 minutes of visual angle just perceptible is approximately 4% at 10,000 ft. L. This is the absolute threshold for two surfaces of the same color,

employing a visual discrimination that is easier than that which will be required on the HUD. The fact that the HUD is green instead of white would be expected to reduce the threshold, but the more difficult nature of the discrimination required would raise it. The combined effect of these variables on the threshold could not be safely estimated.

Naish (1962), in a basic R.A.E. (Royal Aircraft Establishment) study of the head-up display, showed some awareness of the high brightness problem. He had this to say:

"For the display to be seen during an approach to a desert airfield, it would probably be necessary for the I-field to have a brightness of the order of 2,000 ft. lamberts, and for use against sky background somewhat greater brightness would be required in the I-field (approximately 3,000 ft. lamberts), with an upper limit tolerance of the order of 10,000 ft. lamberts."

These figures appear to be much higher than threshold. They seem to be in the appropriate range for comfortable display viewing.

Discussion of the high brightness problem with experts in the field did not solve the problem. Therefore, it appeared necessary to determine experimentally what display brightnesses are necessary against a 10,000 ft. lambert background.

Table 1. Examples of approximate average brightness of sky and earth as viewed from an airplane.
(Adapted from Luckiesh & Moss, 1937; and Morgan, et.al., 1963)

	<u>Millilamberts*</u>
. Sunlit Cloud Approaches	10,000.0
. Thick Clouds, Max	10,000.0
. Snow, Max	10,000.0
. Thin Haze	1,000.0
. Shallow Inland Water	1,000.0
. Deep Clear Water, Day	500.0
. Average Clear Blue Sky	500.0
. Very Clear Sky	250.0
. White Paper One Foot from an Ordinary Candle	1.0
. Snow and Full Moon	.01
. Snow and Starlight	.0001
. Green Grass and Starlight	.00001

*These values represent foot-candles necessary to produce equivalent brightness of a white diffusing surface with a reflection factor of 92.9%.

HUD EXPERIMENT

The purpose of the study was to test the discriminability of the HUD at various brightness levels against a high brightness background. While the equipment was assembled, the effect of different combining glasses and of polarized and unpolarized dark glasses was also assessed.

Equipment

The following equipment was employed in the experiment:

1. High-brightness Xenon Lamp

A 2200 watt Hanovia xenon arc lamp was used as a source to illuminate the high-brightness background of the display. This lamp produced an output of 76,000 lumens over a 10 steradian solid angle. The light produced was white, and of a broad color spectrum, closely resembling sunlight.

2. Auxiliary Lamp Equipment

The lamp required special power (50,000 volt igniter voltage, and 120 amperes of power at 20 volts to run), and was equipped with a special lamp housing (through which air was circulated to cool the lamp and remove ozone produced by the ultra-violet component of the lamp's output), an exhaust fan and hose, and the optical accessories to the lamp. The latter included a heat resistant spherical reflector, ground glass diffusers, and the rear-projection screen which formed the actual background surface against which the displays were viewed.

3. Simulated HUD Display

An operating HUD unit was not available, so a simulated unit producing 20 different HUD display configurations was employed. The simulated HUD included the following:

- a. 750 watt slide projector, used as light source.
- b. Variable density optical filter, which produced a continuous, easily controlled variation of the light passing through it without affecting the color of the light.
- c. A green filter (Corning C. S. 4-64, unpolished), which made the projector light output match closely the color of a P-31 phosphor.¹
- d. Ground-glass diffusers of the projection lamp.
- e. Twenty large HUD display slides representing all possible combinations of four horizon positions and five angles of attack. (See Figure 1) The appropriate slide was easily slipped into and out of place. The dimensions of the display lines were as follows:

Table 2 - Display Symbol Dimensions

<u>Display Element</u>	<u>Size (in.)</u>	<u>Visual Angle (°'s)</u>
Horizon length	3.0*	6.75
Horizon width	.018	.040
Angle of attack symbol length	.20	.440
Angle of attack symbol width	.018	.040

*3.0" at combiner; 2.0" at slide (viewing distance 26")

-
- f. A hand-operated shutter that cuts off the display.
 - g. Collimating lenses and a mirror.
 - h. Combining glass holders, which could be used with any appropriate glass.

¹ At the time of the experiment, it was planned to use a P-31 phosphor on the HUD tube.

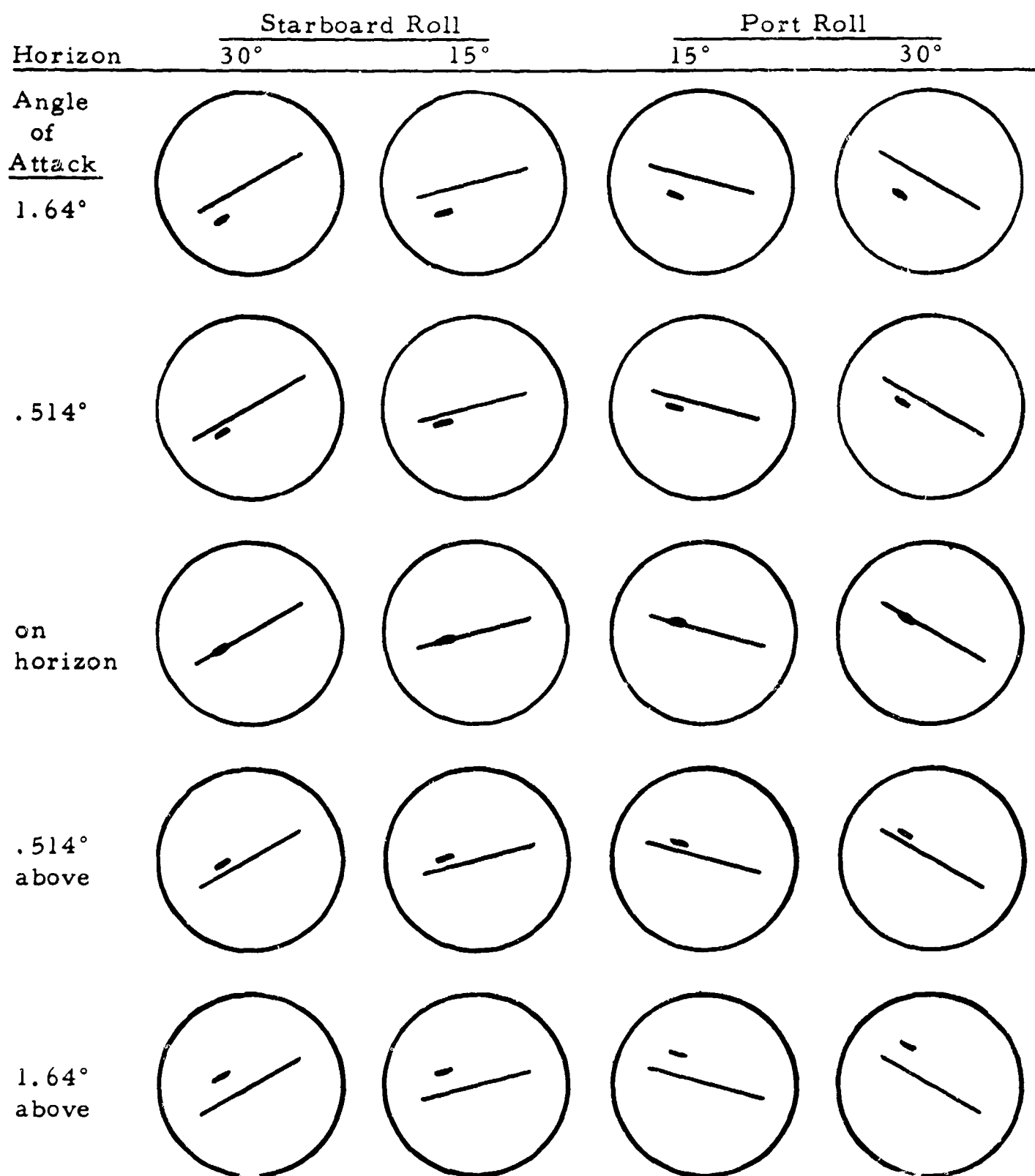


Figure 1 HUD Display Configurations

- i. A chin rest, to properly position the subject's eyes within the exit pupil of the display.

4. Photocell and Voltmeter

A selenium photocell was placed in the projection beam near the display slides, but in a position such that it could cast no shadow on the displays used. The output of the photocell was fed to a digital voltmeter, which operated continuously during the experiment. Readings on this voltmeter for the range of display brightnesses to be employed were calibrated against spot photometer readings of the brightness of the display along the subject's line of sight. It was possible to adjust the brightness of the display to the nearest 10 ft. L. by rotating the variable density filter until the appropriate digital voltmeter reading was obtained.

5. Trichroic and Clear Combiners

Data for any clear combining glass could be generalized to others of different reflectances (i. e., different because of clear non-reflective coatings, etc.). The basic clear combiner used was 3/8" Pittsburgh plate glass, slightly greenish in appearance. A limited amount of data was also gathered using a piece of clear white 1/8 inch window glass having a non-reflectance coating. Reflectance and transmission of several other glasses were measured from the subject's eye position. (See Table 3).

The trichroic glass was designed especially to reflect (i. e., filter out) a very narrow band of green light and to transmit light on both sides of the band. It distorted transmitted colors slightly, desaturating greens and enhancing reds and purples. Photometric data on its reflection and transmission characteristics are included in Table 3 and Figure 2. The latter shows transmission of the percentage of light with blockage centered at about 525 millimicrons in a 50 millimicron wide notch.

Table 3. Photometric Data on Combining Glasses¹ (in per cent)

<u>Code</u>	<u>Glass</u>	<u>Reflectance</u> ²		<u>Transmission</u> ²	
		<u>45°</u>	<u>67°</u>	<u>45°</u>	<u>67°</u>
M	Calibration (front-surface optical mirror)	100	100	0	0
A	Plate (uncoated 3/8")	12	24	85	79
T	Trichroic coated (1/8")	70	(25) ³	60	63 ⁴
X	Partially silvered plate (1/4")	31	31	66	60
W	Window (1/8") anti-reflectance coated	7	21	90	84

¹ 45° measurements made with optical axis vertical, glass at 45°, photometer level; 67° measurements made per "HUD" configuration (Figure 4).

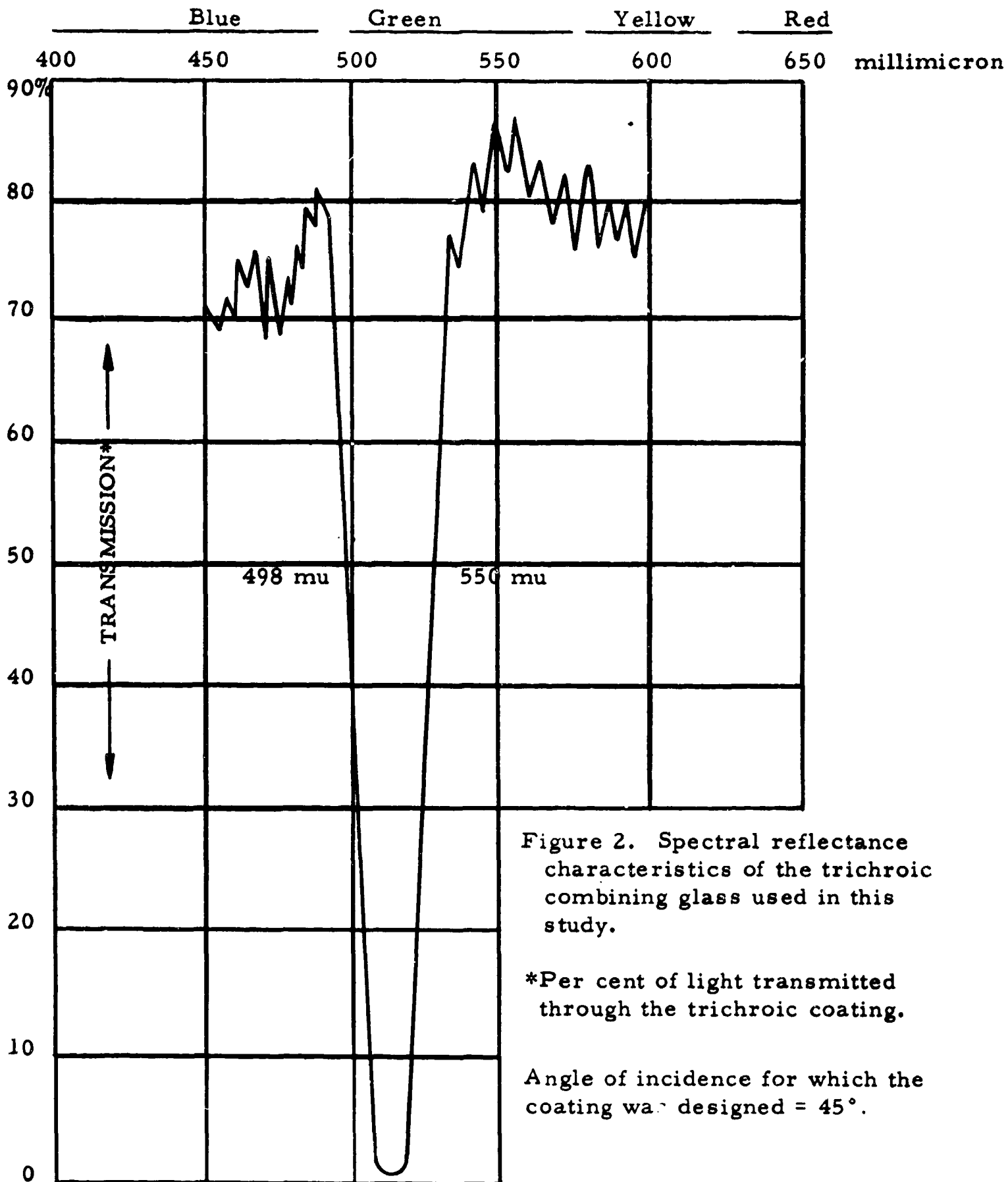
² Reflectance measurement of green display symbol surface; transmission of xenon white background.

³ This trichroic glass was developed for high reflectance at 45°.

⁴ Actual measured transmission does not agree with the 70 to 80 per cent values in Figure 2. The presumed reason for this is that the above transmission values are reduced as a function of the angles used.

6. Photometer

A Spectra spot photometer, filter-corrected to match the human eye, was employed for all brightness measurements, including the calibration of the photocell by means of which display brightness was adjusted.



7. Other Equipment

A stop watch, green polarizing sunglasses, and non-polarizing sunglasses were also employed in the course of the experiment.

Figure 3 illustrates the basic arrangement of the equipment for the 67° measurements, which closely approximated the optical situation for planned use of the HUD. The equipment could also be set up so that light striking the combining glass was moving vertically, and was reflected at 45° . This was necessary because the only trichroic glass available was made to reflect optimally at 45° . After the equipment was built, measurement showed an error of just under 2° in the 67° configuration, which is the reason for the discrepancy between the angular dimensions of Figure 4 (the actual measurements) and of the intended angle of 67° . This small discrepancy only slightly affects the data gathered.

Procedure

The subjects looked through the combining glass into a bright sunburst area some two feet in diameter. The central eight inches of this bright area, which was evenly illuminated, formed the background of the display, the brightness tapering off from the central area to the edges of the sunburst. The subjects were read the following instructions:

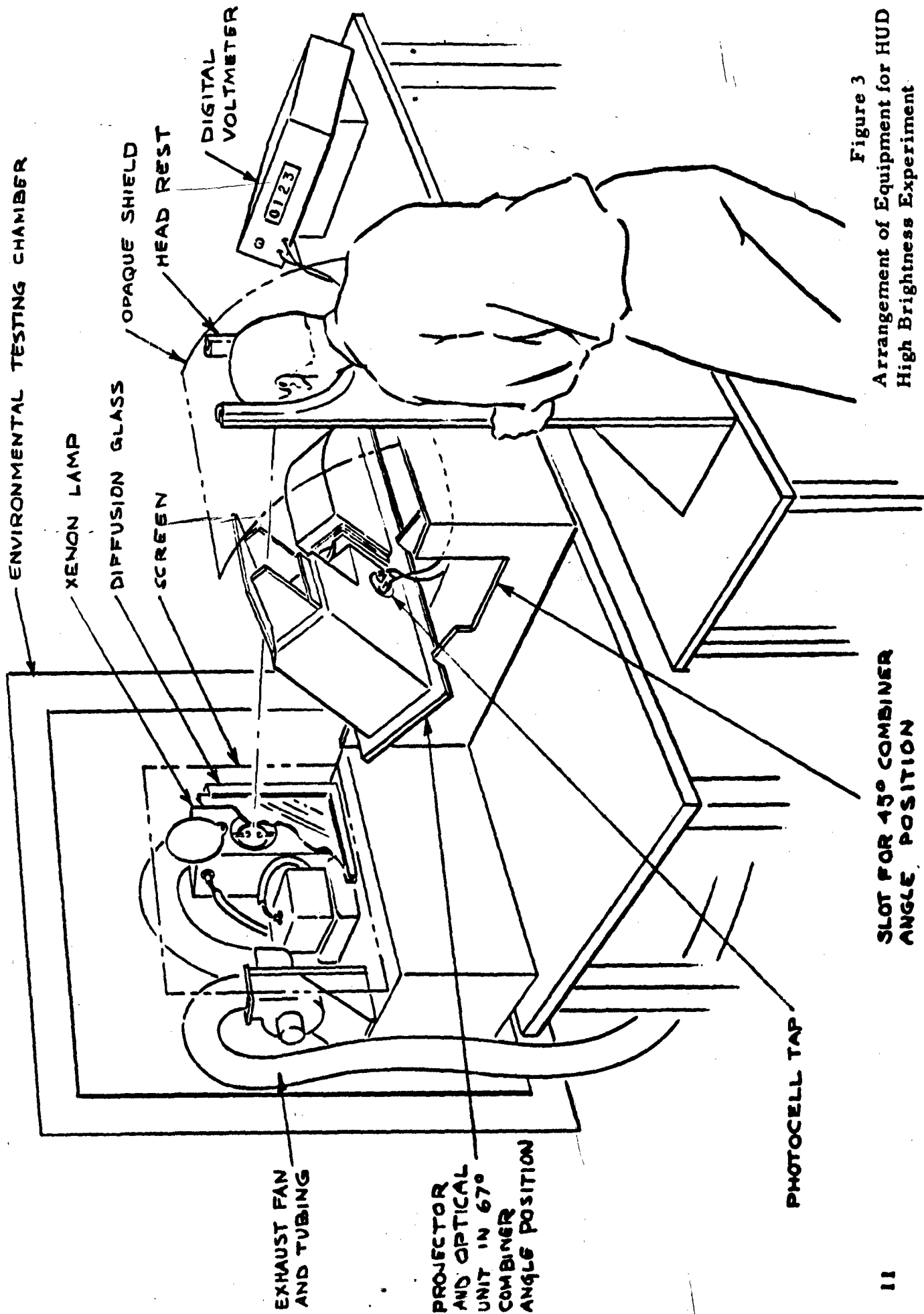
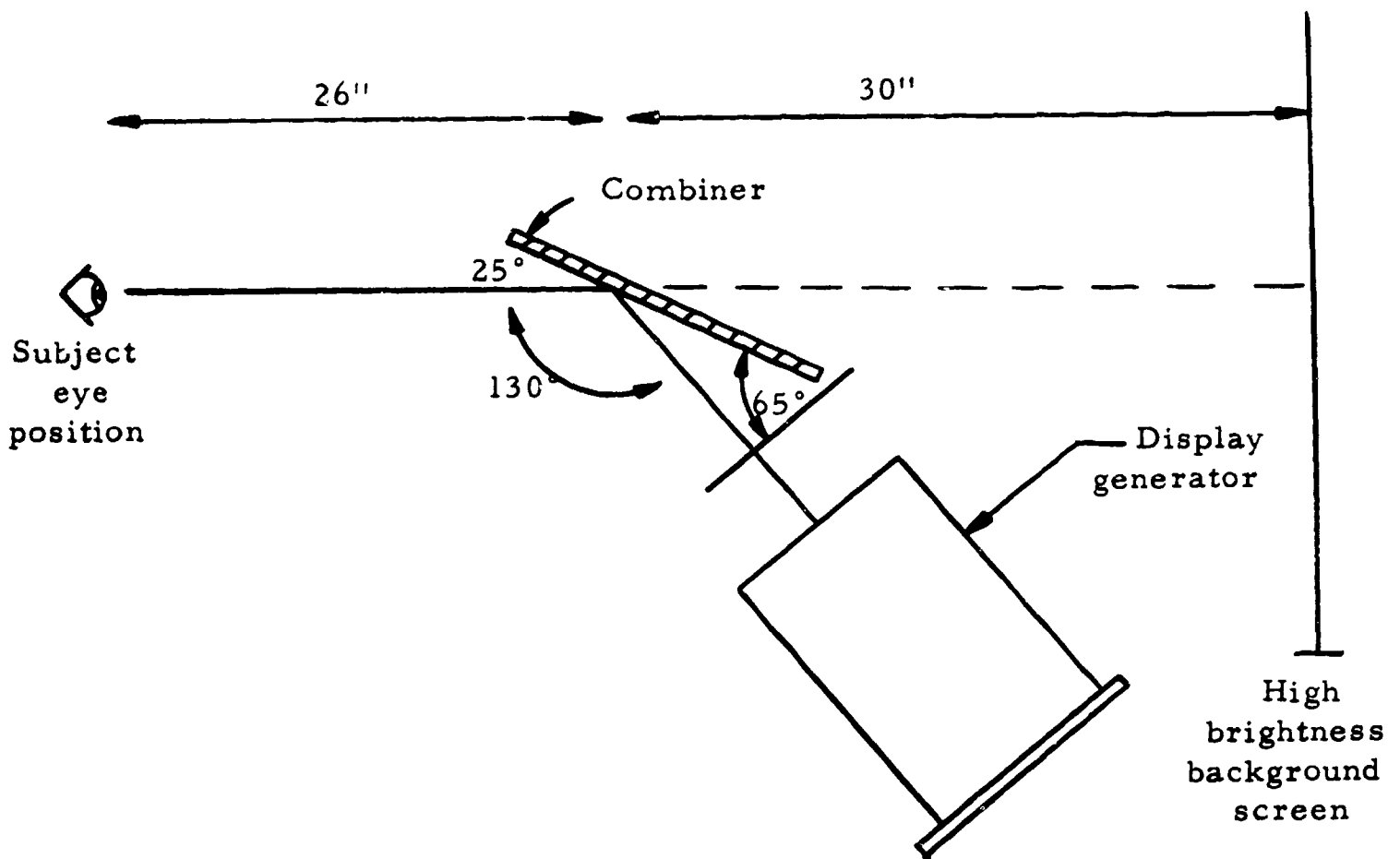
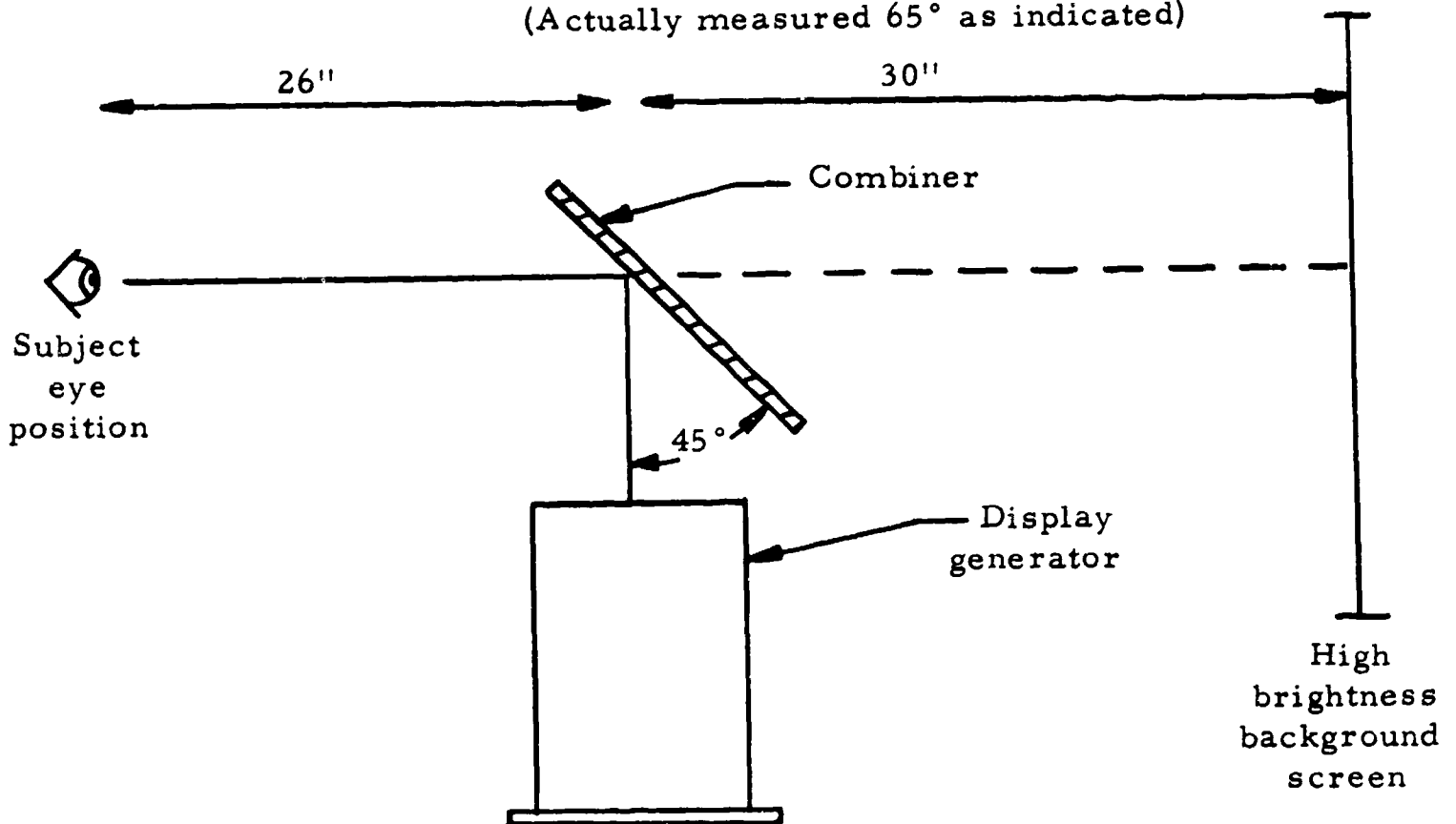


Figure 3
Arrangement of Equipment for HUD
High Brightness Experiment

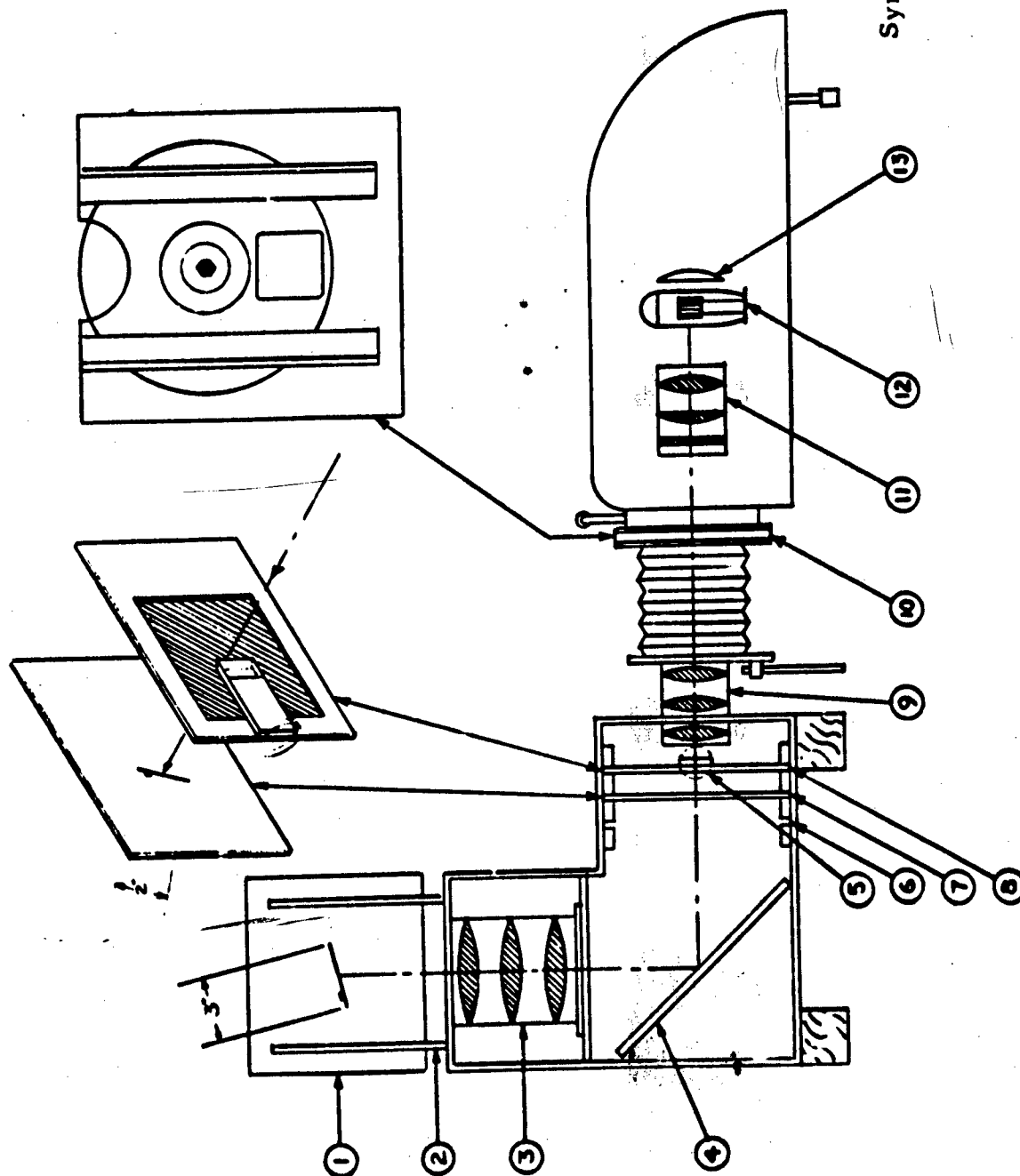


a. HUD (67°) Configuration
(Actually measured 65° as indicated)



b. HUD (45°) Configuration

Figure 4. Optical paths in relation to two combining glass angles.



- ① SELECTED COMBINER GLASS
- ② 45° OR 67° ANGLE FRAME
- ③ COLLIMATING LENS UNIT
- ④ FRONT SURFACED MIRROR
- ⑤ PHOTOCELL
- ⑥ SLOT FOR OPAQUE SLIDE
- ⑦ SYMBOL RETICLE SLIDE
- ⑧ GREEN FILTER WITH PLEXIGLAS STRIP
- ⑨ ADJUSTABLE LENS UNIT
- ⑩ VARIABLE DENSITY NEUTRAL DENSITY FILTER IN PLEXIGLAS HOUSING
- ⑪ PROJECTOR LENS UNIT
- ⑫ 750 W LAMP
- ⑬ REFLECTOR

Figure 5

Symbol Generating Equipment

Instructions

The purpose of this experiment is to see how well you can see head-up display symbols against a very bright background. You will be shown various display configurations of different brightnesses, and will be asked to indicate the display shown. Beside you is a chart showing the display configurations. There are four horizon positions, A, B, C, and D, and five positions of a small line below or above the horizon, 1, 2, 3, 4, and 5 for a total of 20 display configurations. You will be shown these display configurations at random. You will receive a warning, and the display will be flashed on for three seconds, after which you will be asked to name the display as A-3, D-1, C-4, etc. Report the horizon letter when you cannot see the additional small line. Guess when you have the slightest inkling of what the display might be, both on the horizon line and small line. We will have a series of practice trials before we start recording data. Have you any questions?

The displays had been selected to provide an easy display discrimination, the horizon angle, and a difficult one, the angle of attack. The only significance of the latter choice was that it required as fine a discrimination as any on the HUD, save the precise reading of airspeed and altitude scales, which will not often be required under conditions of high brightness backgrounds. Display sequences were randomized so that each of the 20 display configurations was equally likely to occur on any given trial.

Both horizon and angle of attack were scored on each response, but thresholds were taken based on one or on the other in any given series of 50 trials. Thus in measuring the horizon threshold the subject might be entirely unable to see the angle of attack symbol, and in measuring the angle of attack threshold the horizon threshold might never be reached.

The brightness of the display was adjusted after each response. If the response was correct, (on horizon or angle of attack, whichever was being measured) the brightness of the next display configuration

shown was reduced by a set amount, usually 10 ft. L. on the display. When the response was incorrect, the brightness of the next display configuration was increased by 9 times this 10 ft. L. amount (i.e., 90 ft. L. was added). The data so gathered must range around the 90% thresholds, and if steps are small enough, the mean of an extended set of observations would be the 90% threshold.¹ The size of the steps is large enough here that the means will be slight over-estimations of the 90% threshold.

On the order of 15-20 practice trials were given at the outset, so that the subject might adapt to the bright background, and so that a starting point near threshold could be determined.

Subjects were male employees of Kaiser or Dunlap, ages 23 to 35, having normal color vision as measured on Ishihari charts, and who had no history of any sort of vision defect that had been detected.

After gathering threshold data on clear and trichroic glass, the "comfortable range of brightness" of the displays was determined for the two subjects having the highest and the lowest thresholds. Photometric data on the various combining glasses were gathered employing polarizing (anti-glare) and non-polarizing green sunglasses, and a threshold determination was made with the non-polarizing sunglasses, to see if this would change the threshold significantly. (It was not expected to.)

Results

Figure 6 is a graph of a typical run of 50 trials. Note the trials labeled "T", the lowest values reached prior to an error. The "T" trials are averaged to indicate the threshold. They are the brightness at threshold; when the brightness was turned just 10 ft. L. lower, the subject failed to see the display. The "> 90%" threshold, on the other hand, is the average of the final 30 trials, the first 20 being considered a period of hunting for the threshold region.

¹ The 90% threshold is the brightness at which the display is correctly identified 9 times out of 10.

Background brightness: 10,000 ft. L.
 Brightness through combiner: 6,500 ft. L.
 Mean threshold (T readings) 202 ft. L. = 3.12% contrast
 ➤ 90% threshold (mean of last 30 readings)
 252 ft. L. = 3.8% contrast

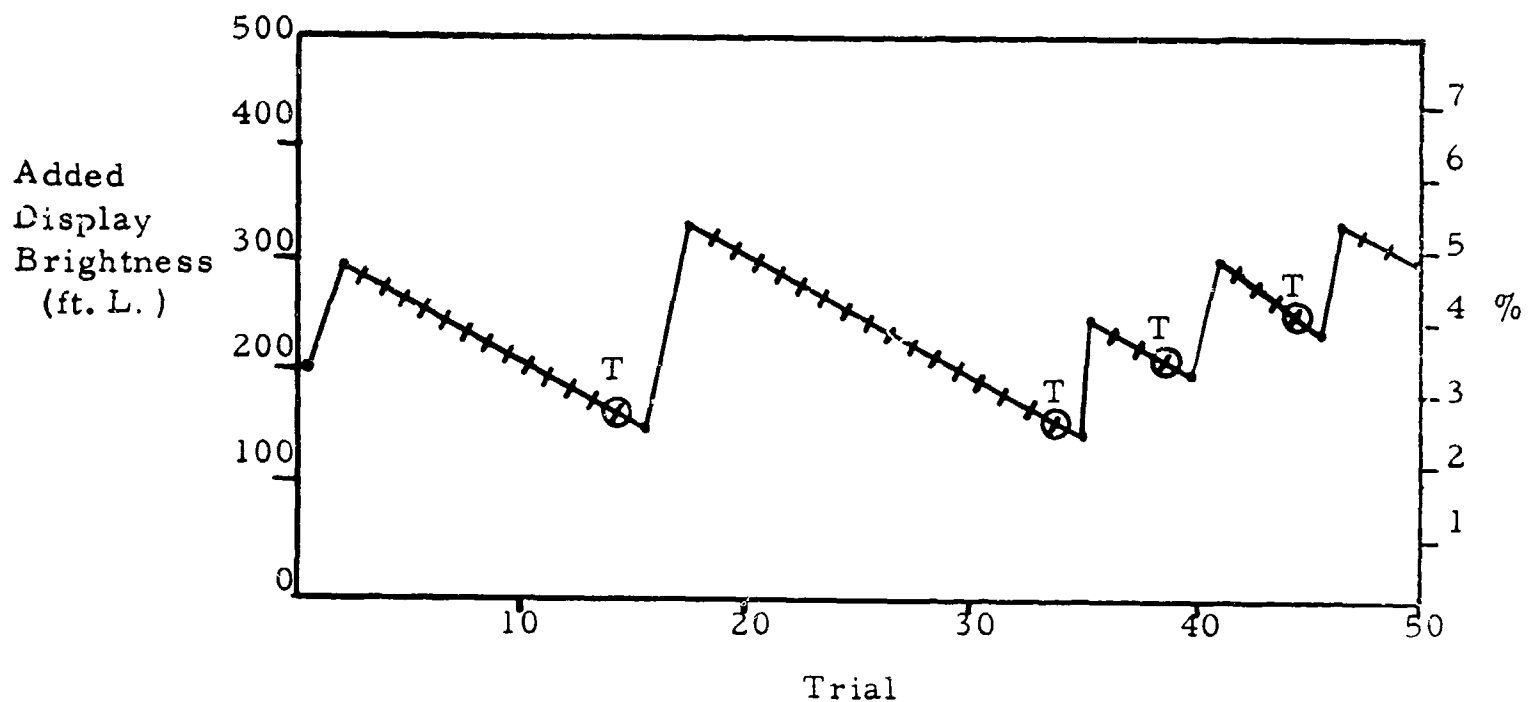


Figure 6. Raw data from a typical run.
 (Trichroic combiner, angle of
 attack display - Run 7, Table 4).

Table 4. Brightness thresholds and per cent contrast for fine (angle of attack) and coarse (horizon angle) head-up display under high ambient illumination. Each of the 20 runs consisted of 50 observations.

Run	Subject	Combiner	Brightness (foot lamberts)			
			Background (Basic)	Thru Combiner	Angle of Attack Display	
					Threshold (mean of all threshold trials)	>90% Threshold (mean of last 30 trials)
1	PHS	A45°	10,000	8,200	598 (7.3%)	683 (8.3%)
2	JK ¹	A45°	10,000	8,200	1065 (13.0%)	1382 (16.8%)
3	HT	A67°	10,000	7,200	380 (5.3%)	456 (6.3%)
4	DR	A67°	10,000	7,200	421 (5.8%)	574 (8.0%)
5	DR	A67°	10,000	7,200	469 (6.5%)	506 (7.0%)
6	JK	A67°	10,000	7,200	762 (10.6%)	792 (11.0%)
7	PHS	T45°	10,000	6,500	202 (3.1%)	252 (3.9%)
8	HT	T45°	10,000	6,500	178 (2.7%)	195 (3.0%)
9	DM	T45°	10,000	6,500	162 (2.5%)	185 (2.8%)
10	JK	T45°	10,000	6,500	264 (4.1%)	312 (4.8%)
<hr/>						
					Horizon Display	
					Threshold	>90% Threshold
11	PHS	A45°	10,000	8,200	261 (3.2%)	321 (3.9%)
12	JK	A45°	10,000	8,200	430 (5.2%)	519 (6.3%)
13	HT	A67°	10,000	7,200	286 (4.0%)	310 (4.3%)
14	DR	A67°	10,000	7,200	360 (5.0%)	392 (5.4%)
15	JK	A67°	10,000	7,200	608 (8.4%)	601 (8.3%) ³
16	PHS	T45°	10,000	6,500	94 (1.4%)	125 (1.9%)
17	DM	T45°	10,000	6,500	152 (2.3%)	225 (3.5%)
18	JK	T45°	10,000	6,500	236 (3.6%)	252 (3.9%)
19	JK	W67°	12,500	10,000	406 (4.1%)	483 (4.8%)
20	[JK ²	W67°	12,500	10,000	370 (3.7%)	459 (4.6%)]

¹ Results may reflect subject fatigue. Data taken at 12:30 a. m., following 16 hours of work.

² Subject wearing unpolarized green sunglasses, transmitting 29% of background and 31% of the display light.

³ Because 90% thresholds are on last 30 trials only, it is possible (though unlikely) for them to be lower than the "threshold" means.

Table 5. Mean display threshold data in per cent for all subjects for plate glass (A) and trichroic (T) combining glasses under 10,000 foot lambert background luminance.

	<u>Plate Glass Combiner</u>		<u>Trichroic Combiner</u>	
	<u>runs</u>	<u>% (mean)</u>	<u>runs</u>	<u>% (mean)</u>
Angle of Attack Display				
<u>Threshold</u>	1, 3, 4, 5, 6 ¹	<u>7.1</u>	7, 8, 9, 10	<u>3.1</u>
> 90% Threshold		8.1		3.6
Horizon Display				
<u>Threshold</u>	11, 12, 13, 14, 15	<u>5.2</u>	16, 17, 18	<u>2.4</u>
> 90% Threshold		5.6		3.1

¹ Run 2, in which the subject was highly fatigued, was omitted.

(Usually it had been located in practice trials.) This method of taking data will provide scores that oscillate about the 90% threshold. (Note that the subject missed on 5 out of 50 trials in Figure 6).

Table 4 summarizes the results for each of the 20 sets of 50 trials. Table 5 groups the data in various ways, and shows averages across subjects. Note that it was not possible to obtain data for all subjects under all conditions. Since there are appreciable individual differences among subjects, the averages are not strictly comparable. These averages are our best estimate of the thresholds we would expect of Navy pilots, but our best comparisons of combining glasses can be made by looking only at data where the same subjects were run under the two (or more) conditions compared. Table 6 contains some pairs of such data.

These tables represent threshold data, i. e., are from exceedingly dim displays. The most and least sensitive subjects were asked what they would consider the lowest comfortable level of brightness for the display for the finer (angle of attack) discrimination. Table 7 contains these data. It also incorporates a reading on the effect of green sunglasses on the display "comfort level."

Table 8 consists of photometric measurements on the various combiners made along the line of sight through green polarizing sunglasses. All combining glasses except the trichroic polarized the light along a horizontal axis, so that the use of anti-glare polarizing sunglasses would substantially reduce the brightness of the display relative to the background, the amount of the reduction depending, as Table 8 shows, on the type and angle of the combining glass employed.

Discussion

The basic questions about the brightness levels required on the HUD display can be answered on the basis of the data collected. If a clear combining glass is employed, pilots will want display contrasts of at least 20 to 35 per cent, i. e., perhaps 1800 to 3500 ft. L. display brightness reflecting from the combining glass, assuming 90% transmission by windscreen and combining glass, and an external background luminance of 10,000 ft. L. The minimum brightness contrast for a barely visible near-threshold display is on the order of 10 per cent, or 900 to 1,000 ft. L. reflected from

Table 6. Mean display threshold data in per cent for matched runs (using the same subjects) for plate glass (A) and trichroic (T) combining glasses under 10,000 foot lambert back-ground luminance.

	<u>Plate Glass Combiner</u>		<u>Trichroic Combiner</u>	
	<u>runs</u>	<u>% (mean)</u>	<u>runs</u>	<u>% (mean)</u>
Angle of Attack Display				
<u>Threshold</u>		<u>8.9</u>		<u>3.6</u>
> 90% Threshold	1, 6	9.6	7, 10	4.3
Horizon Display				
<u>Threshold</u>		<u>4.2</u>		<u>2.5</u>
> 90% Threshold	11, 12	5.1	16, 17	2.9

Ratio of thresholds on plate glass to trichroic combiner (runs 1, 6, 11, 12 versus 7, 10, 16, 18) 6.9:3.3 (> 2:1)

Table 7. "Comfortable" display brightness contrast against high brightness background for most and least sensitive subjects. (In per cent)

<u>Subject</u>	<u>Combining Glass</u>	<u>Per cent Contrast at Minimum "Comfort" Level (%)</u>
PHS	clear	21.9
JK	clear	42.6
PHS	clear with sunglasses ¹	20.0
JK	clear with sunglasses	25.0
PHS	trichroic	13.8
JK	trichroic	18.5

¹ Green, non-polarizing, which transmit 29% of the white background and 31% of the display luminance. Contrast figures are not corrected for this differential transmission, which would modify contrast at the eye by a factor of 1.07.

Table 8. Per cent of background and HUD display luminance transmitted by various combiners through green polarizing (glare reduction) sunglasses, and the resulting effect on display brightness contrast.

Combining glass	Angle	Transmittance ¹		Contrast of unpolarized compared to polarized display ²
		Background	Display	
		Per Cent		Factor
A (3/8" plate)	67°	27	9	3.00 ³
A "	45°	25	5	5.00
T (Trichroic)	45°	25	24	1.04
W (1/8" non-reflect- ance coated)	67°	25	8	3.12
W "	45°	25	15	1.67
X (1/4" partially silvered)	67°	25	5	5.00
X "	45°	25	15	1.67

¹ By comparison, the pair of green non-polarizing sunglasses used in run 20, Table 4 and Table 7, transmitted 29% of the background and 31% of the display.

² Tube brightness must be multiplied by this factor to maintain a given level of display contrast whenever polarizing sunglasses or a polarizing sun shield is used.

³ $27/9 = 3.00$

the combiner. This will provide an extremely dim display, but one that most pilots can be expected to see more than 90 per cent of the time with continuous high background brightnesses.

A "minus green" trichroic coated combiner such as the one tested enhances the display by filtering out real world green in the designated spectral notch (i. e. , only the CRT phosphor green is rejected, other green wave lengths from the real world are allowed to pass). A trade-off situation exists here since a too narrowly specified notch or other requirements leading to a thicker trichroic coating can give a purplish cast to the combiner.

The trichroic coating used in this experiment shows that an equally "comfortable" display need only provide display brightness contrast on the order of 14 to 20 per cent, or 840 to 1200 ft. L. off the combiner, assuming 60 per cent transmission of a 10,000 ft. L. background. A dim trichroic display which most pilots could be expected to see more than 90 per cent of the time under the worst background brightness conditions need provide some 5 per cent brightness contrast, or, under the conditions described 300 ft. L. off the combiner.

If glare reducing polarizing sunglasses or sun shields are to be worn, the display brightness must be increased to compensate for the polarization of the display. The increase is great for clear combiners, 300 to 500 per cent, but only 104 per cent for the trichroic combiner employed in this study.

Sunglasses result in substantially increased comfort in the face of high background brightness, but affect thresholds very little. A direct comparison was made of a subject's performance under identical conditions with and without non-polarizing green sunglasses. The data showed a slight improvement in performance with sunglasses which could be explained entirely as a result of brightness contrast enhancement, since the greenish lenses transmitted 31% of the green display light, but only 29% of the background white. Gray sunglasses might have no effect except to increase the comfort of their wearer.

The brightness delivered to the combiner, in contrast to that reflected from it, will be a function both of threshold data and the combiner's reflectance. The anti-reflectance coated HUD combiner reflects about 15 per cent, while the thicker uncoated plate glass reflects 24 per cent at 67°. The trichroic combiner, however, reflected

Table 9. Tube face brightnesses in foot lamberts for minimum comfortable and near-threshold displays, with and without polarizing sunglasses.

Combining glass	Tube Brightness Required (Ft. L.)			
	Minimum Comfortable Display ¹		Near-Threshold Display ²	
	w/polarizing glasses	w/o polarizing glasses	w/polarizing glasses	w/o polarizing glasses
Trichroic 45°	1,595	1,534	469	451
A(3/8" plate)				
67°	31,184	10,395	10,380	3,465
A45°	111,840	22,368	37,300	7,456
W(1/8" win- dow) 67°	39,409 ³	12,631 ³	13,135 ³	4,210 ³
W45°	67,804	40,601	22,600	13,533
X67°	30,560	6,112	10,185	2,037
X45°	12,274	6,723	3,742	2,241

¹ Assumes minimum comfortable brightness contrast of .17 for trichroic and .30 for clear combiners. w/= with; w/o = without.

² Assumes near-threshold brightness contrast of .05 for trichroic and .10 for clear combiners. A display of this brightness will be very faintly visible to most pilots most (90%) of the time.

³ This glass matches the actual HUD combiner quite closely for these data.

70 per cent of the display luminance when used at the angle for which it was designed, 45° . Assuming only 5 per cent loss via the collimating lenses from tube face to combiner, the tube brightness necessary to produce HUD displays having the contrast characteristics described above are shown in Table 9. These figures were derived using the photometric data of Tables 7 and 8, and assuming the collimating system would transmit 90 per cent of the light from the tube face passing through it. This table is perhaps the most significant statement of the results of the study. To provide a minimum comfortable uncoated HUD display to a pilot wearing polarizing (anti-glare) sunglasses or using a sun shield, a tube brightness on the order of 40,000 ft. L. would be necessary. This value is so far beyond the state-of-the-art, it need not even be considered. If no polarizing glasses or sun shield is employed, a tube brightness on the order of 12,600 ft. L. reaches the "minimum comfortable" level. A display near threshold and much below the level of comfort requires tube brightnesses on the order of 13,000 ft. L. for a pilot with, vs, 4,200 ft. L. for a pilot without polarizing sunglasses or shield.

We conclude that a HUD display similar to the uncoated experimental version would be barely visible against the specified high brightness background, provided the pilot does not wear polarizing glasses or use a polarizing sun shield. However, known CRT's cannot be turned up high enough to make such a display comfortably bright and are believed to have prohibitively short life expectancy at output levels approaching the required brightness. Display symbology would be faintly visible to many pilots most of the time while operating the CRT in the region of 4-5,000 ft. L. However, it must be emphasized that this is not considered a useable brightness range against 10,000 ft. L.

Kaiser investigators are evaluating various techniques to reduce CRT brightness requirements and thus maximize tube life in head-up display applications. Promising design recommendations are being considered but additional experimentation and data collection must be completed before a specific approach is finalized. The scope of this report does not allow for a full development of alternate considerations.

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